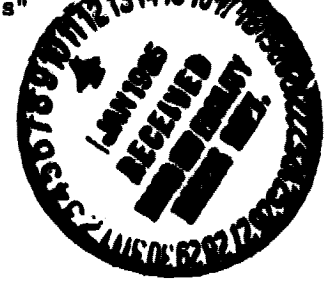


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The research supported by this grant covered two main areas:

1) What were the conditions (composition, temperature-time relationships, etc.) in the solar nebula? What chemical and mechanical processes produced the observed chemical fractionations in the chondrites, the meteorites that originated directly in the nebula? What were the nebula processes that formed the mm-sized spheroidal grains called chondrules?

2) What processes occurred in the parent bodies of the differentiated meteorites? For example, were the volatiles (Na, K, Zn) missing from the basaltic meteorites (eucrites, howardites) lost by outgassing during igneous differentiation, or were they lost during the nebular formation of the (presumably) chondritic starting materials? Did the fractionation of moderately volatile elements (e.g., Ge, Ga, Sb, As, Au) observed in iron-meteorite groups occur in the solar nebula or in a parent-body setting? Did the iron meteorites from each igneous group form by fractional crystallization of a molten core, or did they form as magma plums at widely differing depths in a plum-pudding type parent model?

As often true in natural science, the key to finding answers to such questions is the development of a detailed taxonomy. A major or minor theme in most of our papers has been the development of a detailed classification of all kinds of meteorites.

It is widely held that the solar system formed by collapse of a fragment of an interstellar cloud. The probable if oversimplified sequence of events consisted of: gravitational collapse; conversion of gravitational energy to heat; partial or complete evaporation of interstellar solids; cooling as a result of radiative losses; condensation; mechanical interactions between grains leading to growth of some by adhesion and the decrease in the size of others as a result of brittle fracturing; "settling" of grains to the nebula median plane. Finally and poetically, another gravitational collapse produced planetesimals having dimensions of ~100 m from these median-plane grains. These planetesimals had all the properties of the primitive chondrites (meteorites having relative concentrations of nonvolatile elements which are solar, i.e., essentially the same as those measured in the solar

meteorites rarely fall because the initial amount was smaller, and because they had space survival lifetimes similar to those of stony meteoroids (~ 15 Ma), much less than the ~ 600 Ma survival lifetimes of irons.

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atmosphere) except the strength required to penetrate the Earth's atmosphere. This was probably achieved as a result of compaction and minor reheating during collisions.

A major fraction of the research and this grant was devoted to gathering data on the components of chondrites and interpreting these data in terms of the processes discussed above. Even the differentiated meteorites preserve a partial record of the chondritic materials from which they formed; for example, siderophile/Ni ratios in the iron meteorite cores were probably closely similar to ratios in the chondritic precursors.

Starting with the Wasson-Chou (1974) paper we have carried out a series of studies attempting to explain the observed patterns of moderately volatile elements in chondrites and iron meteorites; earlier models by Anders (1964, 1968) involving loss of volatiles during the formation of chondrules (mm-sized igneous spherules) did not predict the observed patterns and theoretical arguments indicated that volatile loss would be negligible during a brief heating event. The suggestion of Wai and Wasson (1977) that the lost volatiles were in low-temperature nebular phases that incompletely accreted is supported by a strong correlation between the abundances of the volatiles relative to those in the volatile-rich CI chondrites and their calculated nebular condensation temperatures.

Our studies (Grossman et al., 1979; Grossman and Wasson, 1982) show that volatiles are not systematically depleted in chondrules, consistent with but not confirmatory of our model. These are the first reports of an extensive study program on the chondrules in the highly unequilibrated chondrites, the meteorites that best preserve the record of conditions in the solar nebula. An innovative feature is that following neutron irradiation we saw off a small fraction of each chondrule from which a thin section is prepared for petrographic examination.

Our most important conclusions Grossman and Wasson (1982; 1983a) are that the chondrules formed from random mixture of several nebular components. Grossman and Wasson (1983b) characterized one of these, the refractory lithophile component. During recent years there has been frequent speculation about solid nebular components, but the firm evidence for these has been provided by the cm-sized refractory inclusions in the CV chondrites. Our work represented the first resolution of these components on the basis of precise multielement data on small samples (chondrules in this case) of

chondrites in which these components are not present as isolatable entities.

A surprising discovery was that volatile-element abundance patterns in some iron-meteorite groups are essentially identical to those in chondrite groups. This probably means that (a) the bulk planet had a chondritic composition and (b) that no volatile loss occurred during core formation. We propose that the volatile patterns were established during the same process -- incomplete accretion of low-temperature nebular phases -- responsible for the volatile patterns in the chondrites. Since the 1950s it has been recognized that Ga and Ge have wide ranges among all iron meteorites but are "quantized" in individual iron meteorite groups. Wai and Wasson (1979) recently found the explanation: these are the two most volatile siderophiles and the wide total range results from differences in the amount of volatiles trapped in the precursor solids at the end of nebular condensation and grain agglomeration, the quantization from the fact that they have solid-liquid distribution ratios near 1, thus do not fractionate during crystallization. Malvin et al. (1984) later reported evidence that Cu shows a similar behavior, though the total fractionation is somewhat smaller.

A recent thrust in our research is the study of individual phases in the highly unequilibrated ordinary chondrites. Our interest in these "unequilibrated" ordinary chondrites was stimulated by an accidental discovery; we used the electron microprobe to determine Co in the α (low-Ni) Fe-Ni phase in chondrites showing similar degrees of silicate disequilibrium (similar variances in $\text{Fe}/(\text{Fe} + \text{Mg})$ ratios) in the hopes of improving their classification in (Afiattalub and Wasson, 1980). We were surprised to find great differences in the degree of disequilibrium in the Fe-Ni, and inferred that the chondrites showing the highest degrees of metal disequilibrium had preserved the nebular record better than any other ordinary chondrites. This interpretation soon found support in a study of thermoluminescence sensitivity by members of my research group (Sears et al., 1980). Rambaldi and Wasson (1981; 1982; 1984) studied the metal in several of these most unequilibrated meteorites, and found numerous previously uncharacterized phases and phases assemblages that must each be explained by a combination of nebula processes including chondrule formation. One of the most striking discoveries was that many metal grains contain Si, which we interpret to be a relict of nebula condensation at high temperatures (Rambaldi et al., 1980).

The meteorites that formed by igneous processes account for only about 10% of observed falls. A major early success of our research group was the

development of a detailed taxonomy of iron meteorites based on structure and precise compositional data, and we continue to apply these techniques to additional meteorites (Kracher et al., 1980). The fractionations observed within most iron meteorite groups (e.g., refractories such as Ir vary by factors as large as 6000, and are always negatively correlated with Ni) are consistent with formation by fractional crystallization of initially molten cores. A problem for this model has been the wide and Ni-correlated range of cooling rates inferred from Ni gradients in the two coexisting Fe-Ni alloys for certain groups, IVA in particular. Willis and Wasson (1978a; 1978b) redetermined the cooling rates using new Ni measurements and improved estimates of the effect of P on the phase diagram and on the Ni diffusion coefficient in the low-Ni alloy, and found no cooling-rate variation across the group, consistent with a core origin. However, our conclusions are not accepted by all workers in the field.

Since 1968 we have recognized that the fractionation patterns within the large iron meteorite group IAB (and the minor group IIICD) were distinctly different from those in the remaining groups, all of which seem to have formed by fractional crystallization. Although we and others have proposed models (ours called for formation by grains sticking together in the nebula), it was widely recognized there were serious flaws in all. I have probably spent more time discussing and thinking about this problem than about any other. Thus it is especially satisfying that in a recent paper we could propose a new model involving the impact melting of chondritic parental materials which I am confident is generally correct although surely requiring improvements in its details (Wasson et al., 1980).

For many years it has been recognized that the iron meteorites contain too little of the major element S. In chondritic materials the S/Fe atom ratio ranges from 0.1 to 0.5, and S is in the S^{2-} chemical form that should be efficiently extracted into a metallic melt. As discussed above, other elements of similar volatility are present in some iron-meteorite groups at chondritic abundance levels, but S abundances in these same groups are $\sim 10\times$ lower. After discussing this problem for several years, Kracher and Wasson (1982) proposed a plausible solution: that the heating of asteroids generated two metallic magmas, the first formed at low temperatures and Fe-S rich, the second at high temperatures and low in FeS. The magmas crystallized separately, and each generated meteoroids, but the FeS-rich

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